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THERMAL PERFORMANCE OF A RHENIUM-NIOBIUM CYLINDRICAL THERMIONIC CONVERTER

by R. M. Williams and W. J. Bifano

Lewis Research Center

Cleveland, Ohio

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ABSTRACT

Efficiency and steady-state performance were measured for a cylindrical thermionic converter having a rhenium emitter and a niobium collector. Measurements were made at the cesium-reservoir temperatures at which peak output power was obtained from emitter temperatures in the range from 1873 to 2073 K and collector temperatures in the range from 850 to 1050 K. Increasing the emitter temperature from 1873 to 2073 K resulted in increasing the maximum electrode efficiency from 0.127 to 0.144. The output power at maximum efficiency increased from 5.7 to 9.2 W/cm^2. For fixed emitter temperatures, the emitter-to-collector heat flux increased linearly with current at the rate of 2.10 W/A.

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SUMMARY

A cylindrical thermionic converter with a rhenium emitter and a niobium collector was operated under steady-state conditions. Efficiency and steady-state electrical performance were measured over an emitter temperature range of 1873 to 2073 K and a collector temperature range of 850 to 1050 K. The cesium reservoir was held at the temperature for which peak output power was obtained.

The results show that maximum electrode efficiency increases from 0.127 to 0.144 as emitter temperature increases from 1873 to 2073 K. Over the same emitter temperature range, output power density at peak electrode efficiency increases from 5.7 watts per square centimeter at 0.55 volt to 9.2 watts per square centimeter at 0.85 volt. At emitter temperatures of 1873 and 1973 K, emitter-to-collector heat flux increases linearly with increasing converter current density at the rate of 2.10±0.26 watts per ampere.

INTRODUCTION

Nuclear reactor thermionic systems are potential candidates for space missions requiring either auxiliary or propulsive power. Conceptual designs have been proposed in which the thermionic converters are located either in or out of the reactor core. In the in-core designs, the emitter of the converter serves as the cladding of the nuclear fuel, while in out-of-core designs, the converters are located in either a heat exchanger or the system radiator. In either case, the converters are generally of cylindrical geometry.

The weight and efficiency of the power system are strongly dependent on converter performance. At present, there are very little experimental data available for cylindrical converters. One exception is the data reported in 1963 (ref. 1) which were obtained for two converters having tungsten emitters. Furthermore, as reported in refer-

erce 2, a number of such converters have been tested for long periods of time at fixed electrode and cesium-reservoir temperatures.

Much of the thermionic diode research effort is now directed toward improving diode performance through refinements in electrode surface preparation and converter processing procedures. As new procedures are developed, a continuing program of experimental evaluation is required in order to establish the effect of these procedures on converter performance and consequently on thermionic system performance.

In reference 3, the electrical performance presented for a cesiated cylindrical thermionic converter having a vapor-deposited rhenium emitter and a niobium collector was based on pulse measurements of its current-voltage characteristics; operating conditions resulting in maximum power were emphasized. In the study reported herein, the power density and efficiency of the same thermionic converter are presented as determined from steady-state measurements; operating conditions resulting in maximum efficiency are emphasized. Data for cesium-reservoir temperatures at which peak output power was obtained are presented for an emitter temperature range of 1873 to 2073 K and a collector temperature range of 850 to 1050 K.

SYMBOLS

e	electron charge, C
I	converter current, A
k	Boltzmann constant
Q_{CHTR}	collector heater power, W
Q_E	net power leving emitter, W
Q_{HX}	power measured at heat exchanger, W
Q_{IN}	total ac and dc power to emitter filament, W (Converter Power Loss Terms)
Q_{INL}	total filament power losses through radiation and conduction, W
Q_{LCL}	lower collector lead loss, W
Q_{LEL}	lower emitter lead loss, W
Q_{PL}	plasma loss, W
Q_{UCL}	upper collector lead loss, W
Q_{UEL}	upper emitter lead loss, W
Q_c	thermal power delivered to collector, W
T	electrode temperature, K

V	converter electrode voltage, V
ϵ_C	total emittance, collector
ϵ_E	total emittance, emitter
ϵ_{EC}	total effective, emitter-collector
η	electrode efficiency
ψ_E	emitter electron potential barrier, V

CONVERTER DESIGN AND INSTRUMENTATION

The cylindrical converter tested in this program was built for NASA Lewis Research Center by the Thermo Electron Corporation. The design features are reported in detail in reference 3. A cross-sectional drawing of the converter is shown in figure 1 and a brief description of the converter is presented below.

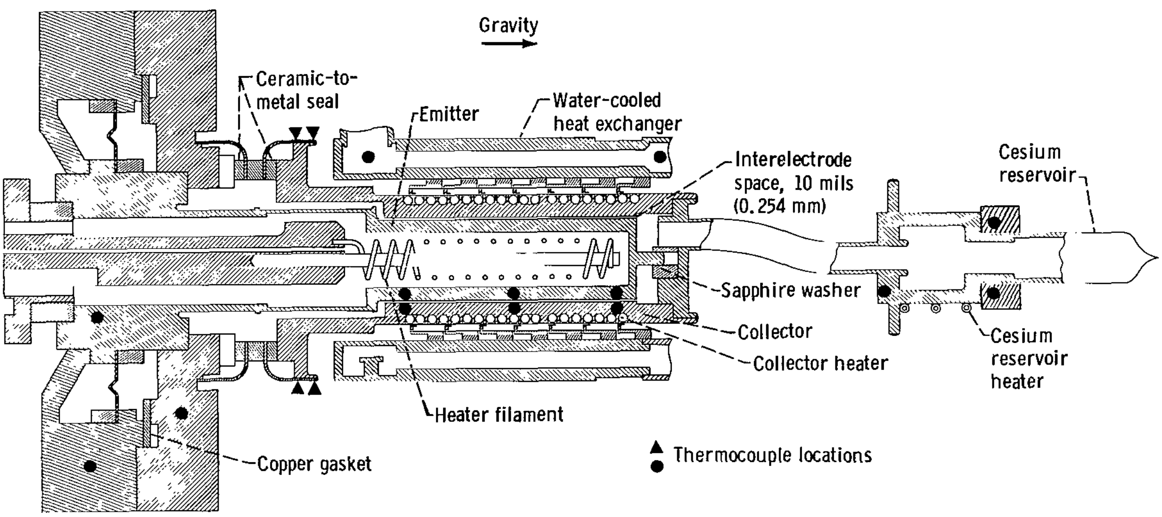

Figure 1. - Cylindrical thermionic converter showing thermocouple locations.

The emitter surface is rhenium vapor-deposited onto a tantalum substrate. The rhenium thickness is nominally 0.38 millimeter (15 mils), and the total emitter wall thickness is 2.03 millimeters (80 mils). The emitter's effective axial length is 3.81 centimeters (1.50 in.) and its outer diameter is 1.28 centimeter (0.502 in.), resulting in an active emitter area of 15.2 square centimeters (2.36 in.^{2}). The mechanically polished emitter is heated by electron bombardment.

The niobium collector is positioned so that it is coaxial to the emitter with a 0.25-millimeter (10-mil) spacing between the two electrodes. At the upper end of the structure, a ceramic-to-metal seal electrically isolates the emitter from the collector, while at the lower end, a sapphire insulator performs the same function. The collector wall is 3.56 millimeters (0.140 in.) thick and its electrode surface was honed and mechanically polished. Two heaters are brazed into grooves cut into the outer surface of the collector structure. These heaters are used to maintain constant collector temperature over a broad range of diode current. Outboard of the collector structure are seven annular fins which act as heat chokes and also relieve the thermal stresses that developed between the collector and the water-cooled copper heat exchanger.

A total of 18 thermocouples was installed in the converter. The location of each thermocouple is shown schematically in figure 1. Three thermocouple wells were provided in the emitter wall for the insertion of W-5Re/W-26Re thermocouples for measuring the emitter temperature at axial distances of 0.38, 1.97, and 3.62 centimeters (0.150, 0.775, and 1.425 in.) from the top of the emitter. Three sheathed Chromel-Alumel (CA) thermocouples were inserted radially into the collector wall to measure the collector temperature at the same axial positions as the corresponding emitter thermocouples.

Cesium-reservoir temperature was measured with two Chromel-Alumel thermocouples inserted into a copper ring fastened to the reservoir. The temperature rise of the water flowing axially through the heat exchanger was measured by two iron-constantan thermocouples which were inserted axially a distance of 15. centimeters (6 in.) into the coolant water lines entering and leaving the heat exchanger. The major portion of the heat rejected from the collector was calculated from the measured water flow rate and the measured increase in water temperature.

Additional thermocouples were used to measure temperature differences across various parts of the converter in order to determine heat losses which were required for the efficiency calculations. Thermocouples were also provided to monitor temperatures of various converter subassemblies such as the metal-to-ceramic seal.

TEST EQUIPMENT

The converter electrode voltage was set and controlled by the circuit shown in figure 2. This circuit is basically a variable electrical load incorporating a water-cooled resistance and a dc power supply. At high converter output currents, the voltage drop in the converter leads is significant in relation to converter output; the variable dc power supply was used to compensate for this voltage drop. Thus, the converter electrode voltage is fully adjustable from open-circuit to zero, provided only that the 240-ampere rating of the emitter lead is not exceeded.

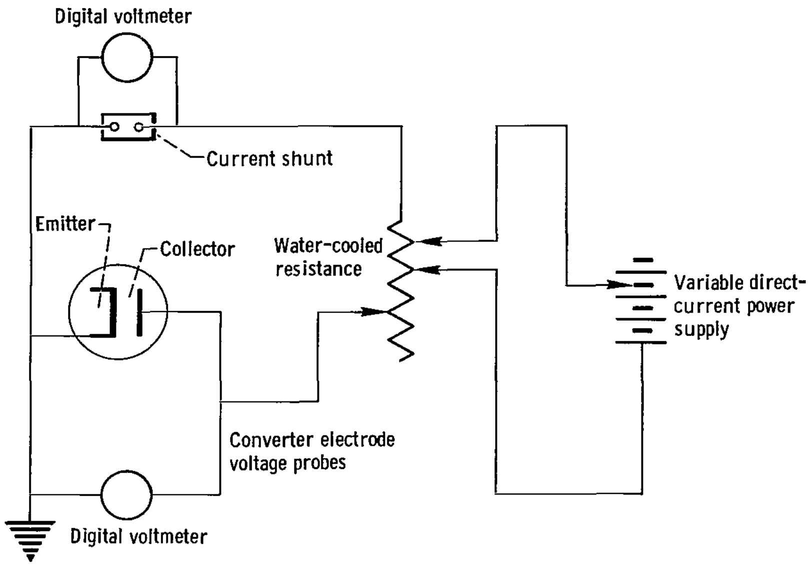

Figure 2. - Data-taking circuit.

A four-digit digital voltmeter was employed to read the electrode voltage and the converter current. Probes were attached to the emitter and collector structures for the electrode voltage measurements. A series of six current shunts was used in the circuit to measure the converter current over a wide range of values.

Collector and cesium-reservoir thermocouples were referenced to a 339 K (150° F) oven, while the three W-5 Re/W-26 Re emitter thermocouples were referenced to room temperature. These thermocouple outputs were scanned and read by the digital voltmeter. Strip-chart recorders were also provided to indicate temperature trends and record the less important thermocouple readings. The total ac and dc power supplied to the emitter by the electron-bombardment heater and the power to the collector heater were recorded. The water flow rate through the collector heat exchanger was measured by a vertically-mounted float-type flowmeter. The accuracy of these measuring instruments and resulting error in the performance values are discussed in the Precision of Data section.

EXPERIMENTAL PROCEDURES

Data Selection and Acquisition

In searching for the converter's operating conditions producing either maximum power or maximum efficiency for any given emitter temperature, the investigator must explore ranges of the other selected independent variables, viz, collector temper-

ature, voltage output, and cesium-reservoir temperature. Because the number of test points can be quite large with four independent variables and because a substantial amount of test time is required for each converter test point, some method for reducing the number of test points is highly desirable. Although the somewhat arbitrary but nevertheless conventional method used here for reducing test time must be described, some required terminology must first be defined.

In the discussions which follow, the terms "peak" electrode efficiency and "peak" power density specify the highest values achieved for given values of both emitter and collector temperatures. The terms "maximum" electrode efficiency and "maximum" power density specify the highest values achieved for a given emitter temperature. In other words, for a fixed emitter temperature, the maximum power density is the highest value of peak power density achieved over the range of collector temperatures considered.

Values for the independent variables were selected in the following sequence. For any selected combination of emitter and collector temperatures, the pulse technique described in reference 3 was used in order to determine the voltage output and cesium-reservoir temperature corresponding to peak power output. (One cycle of a 60-Hz variable-amplitude sinusoidal voltage was superimposed on a steady average voltage applied across the converter's terminals, and the current-voltage response of the converter was recorded on an x-y oscilloscope.) The cesium-reservoir temperature obtained for each combination of emitter and collector temperature was thereafter always used with that combination of emitter and collector temperatures, the resulting cesium-reservoir temperatures being given in table I.

The converter's steady-state performance was then measured for each combination of emitter and collector temperatures in table I, cesium-reservoir temperature being selected as just described. For each such combination of temperatures, converter volt-

TABLE I. - CESIUM-RESERVOIR TEMPERATURES SELECTED TO PRODUCE PEAK POWER FOR EACH COMBINATION OF EMITTER AND COLLECTOR TEMPERATURES

Emitter temperature, K	Cesium reservoir temperature, K				
	850	900	950	1000	1050
	Collector temperature, K				
1873	593	598	598	603	598
1973	598	603	608	608	603
2073	613	613	613	613	---

age was adjusted until peak efficiency (or alternatively, peak power) was obtained. However, the emitter lead's current limitation prevented operation at peak power for all emitter temperatures except 1873 K, the lowest value investigated. For each emitter temperature, the collector temperature corresponding to maximum efficiency (or maximum power) could then, of course, be selected.

Even though cesium-reservoir temperature was selected to produce peak power, the maximum efficiency obtained by this testing sequence was indistinguishable from the efficiency attainable if cesium-reservoir temperature were selected for peak efficiency rather then for peak power. From the data of reference 4, the sensitivity of efficiency to changes in reservoir temperature was estimated; the calculations showed that the efficiency change was less than the uncertainty in measured efficiency.

For each of the fourteen selected conditions, the converter was brought to temperature and an electrode voltage was set by adjusting the load circuit. After the converter reached a steady state, all data necessary to determine thermal and electrical performance were recorded. The electrode voltage was then changed and adjustments were made to maintain the same average electrode temperatures and the data again recorded. This process was repeated until a sufficient range of voltages was covered to fully document the performance.

Method of Efficiency Calculation

The electrode output power of the converter is equal to the product of the converter current I and the output voltage V measured at the electrodes. The electrode efficiency η is defined as follows:

$$\eta = \frac{IV}{Q_E} \tag{1}$$

where Q_E is the net thermal input power to the emitter. A schematic diagram of the converter showing the heat-transfer nomenclature used in determining electrode efficiency is presented in figure 3. The net thermal input power to the emitter Q_E is the sum of the electrode output power IV and the net thermal input power to the collector; that is,

$$Q_E = IV + Q_{HX} + Q_{UCL} + Q_{LCL} - Q_{CHTR} \tag{2}$$

where it is assumed that the thermal end losses from the plasma Q_{PL} are negligible.

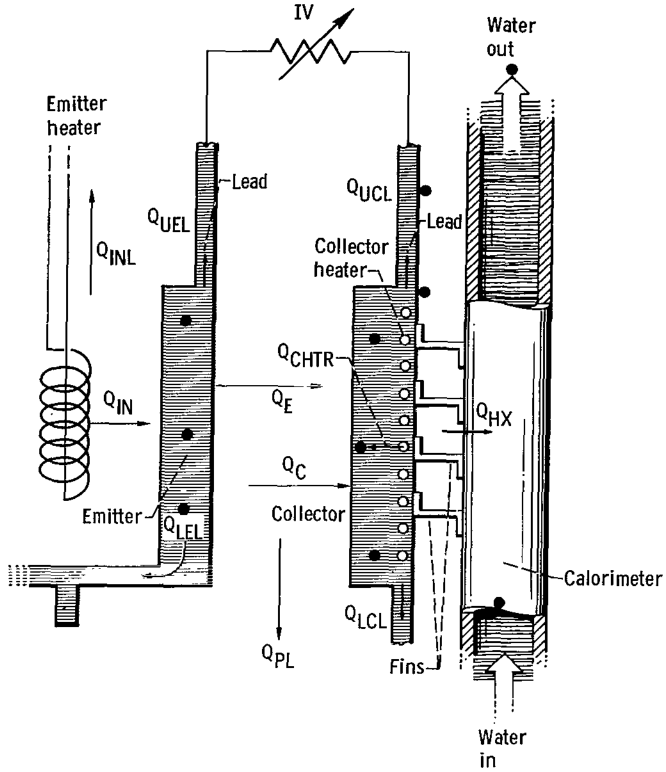

Figure 3. - Converter showing heat-transfer nomenclature.

The major portion of the collector thermal power flows into the water-cooled heat exchanger and is determined from the measured water flow rate and temperature rise. This quantity is denoted Q_{HX}. The remainder of the heat transferred to the collector is conducted through the collector lead and collector support structure. Q_{UCL} and Q_{LCL} are defined as the upper and lower collector thermal losses, respectively. Since this heat loss cannot be measured directly, it was necessary to perform preliminary calorimetric measurements to determine collector end losses as a function of temperature gradients measured at the appropriate locations. The heat input to the collector from the collector heater Q_{CHTR} is determined from measurements of the electrical input power to the heater. This power, which is supplied to control the temperature of the collector, also contributes to the thermal input to the heat exchanger and appears as a negative quantity in equation (2).

Thus, the net thermal input power to the emitter, Q_E, is determined indirectly. The gross thermal input power to the emitter Q_{IN}, from the eleotron-bombardment filament was not used to determine Q_E, since unknown amounts of thermal power are lost by radiation from the emitter cavity, conduction through the filament leads, and conduction through the upper and lower sections of the emitter-support structure.

PRECISION OF DATA

The accuracy of each thermocouple reading, measuring instrument and measured quantity used in the calculation of electrical and thermal performance is listed in table II. Limit-of-error ranges are used in the presentation which are twice the probable-error ranges.

TABLE II. - ERRORS ASSOCIATED WITH THERMOCOUPLE READINGS

Location	Thermocouple type	Thermocouple error	Instrument error	Total error
Emitter	W 5Re/W 26Re	±30 K at 2000 K	DVM±0.01 mV ≈ 0.7 K	[a]±55 K at 2000 K
Collector	Type K Chromel-Alumel	±0.75 percent	Strip chart recorder, ±2.5 K	[a]±20 K at 1000 K
Cesium reservoir	Type K Chromel-Alumel	±0.75 percent	DVM±0.01 mV, (±0.28 K); reference oven, ±0.55 K (±1° F)	3.0 K at 630 K
Heat exchanger water inlet-outlet	Type J Iron constantan	±0.75 percent	DVM±0.001 mV, ±0.019 K (±0.034° F); reference oven, ±0.55K (±1° F)	±0.78 K at 311 K (±1.4° F at 100° F)

[a]This includes uncertainty in the electrode temperatures due to grouping of data, that is, ±25 K for the emitter temperature and ±12 K for the collector temperature.

Thermo Electron Corporation performed the calibration of the W-5 Re/W-26 Re thermocouples. At 2000 K, the limit-of-error range for the temperature reading is estimated to be ±30 K. This temperature error is much greater than the measuring instrument's sensitivity which is equivalent to ±0.7 K.

The effective electrode temperature (emitter or collector) is calculated by area-averaging the three thermocouple readings for that electrode (ref. 3). There is a practical problem of maintaining this effective temperature for a large range of converter voltage settings. Consequently, all data within ±25 K of the quoted effective temperature (i.e., 1873, 1973, or 2073 K) are grouped with the quoted values. Similarly all data within ±12 K of the effective collector temperature (i.e., 850, 900, 950, 1000, 1050 K)

TABLE III. - PRECISION OF DATA (ELECTRICAL PERFORMANCE)

Item	Instrument error	Limit of error
Diode voltage	DVM, ±0.001 V	±0.001 V
Diode current	DVM, ±0.1 A Shunt, ±0.04 percent	±0.2 A at 250 A 0.01 A/cm^2 at 16 A/cm^2
Diode power	-------------------	152±0.4 W at 0.8 V

are grouped with the quoted value. This affects the precision of the data accordingly and this is shown in table II.

The accuracy with which the electrode efficiency can be determined is dependent upon the accuracy of the measurement of each of the terms in equation (1). The error associated with measuring converter output power is presented in table III where it is shown, for example, that there is an error of ±0.4 watt at an output power of 152.0 watts at 0.80 volts.

TABLE IV. - LIMIT OF ERROR OF TEMPERATURE RISE OF HEAT

EXCHANGER WATER FOR REPRESENTATIVE CASE

[Limit of error in temperature difference ±0.11 K (±0.2° F).]

Sources of error	Outlet temperature, K (°F)	Inlet temperature, K (°F)	Effect on temperature difference, K (°F)
Temperature errors	310.9 (100.0)	299.8 (80.0)	11.1 (20.0)
Digital voltmeter (±0.001 mV)	±0.019 (±0.034)	±0.019 (±0.034)	±0.038 (±0.068)
Reference oven[a] (338.8±0.55 K or 150°±1° F)	±0.55 (±1)	±0.55 (±1)	0
Uncertainty of wire calibration[b] (±0.75 percent)	±0.208 (±0.375)	±0.292 (±0.525)	±0.0835 (±0.150)

[a]Both thermocouples are referenced to same oven, consequently error does not affect difference.

[b]The error of thermocouples made from the same spool of wire are in the same direction.

In table IV, the measurement accuracy of the temperature rise of the coolant water is shown for a typical case. The two type-J iron-constantan thermocouples were manufactured from wire from the same spools, referenced to the same 339 K (150° F) oven and their voltage outputs read to ±1 microvolt by a four-digit digital voltmeter. For the example shown in table IV, a 0.11 K (0.2° F) error is expected in the measured 11.1 K (20.0° F) temperature rise of the coolant water.

Tabulated in table V are the errors associated with measuring the collector-lead losses, the coolant-water-flow rate, and the collector-heater power. Also shown is the influence of all the errors on the accuracy of the electrode efficiency for two cases; for the maximum-efficiency points at 1873 and 2073 K, the limit of error in efficiency is 0.007, or 6 percent of the measured efficiency.

TABLE V. - ADDITIONAL TERMS AFFECTING PRECISION

OF EFFICIENCY MEASUREMENTS

(a) Collector losses

Location	Range of loss values, W	Limit of error, W
Upper collector	10 to 20	±8
	20 to 40	±7
Lower collector	40 to 60	±1
	0 to 14	±4

(b) Errors

Instruments	Instrument error	Reading error	Limit of error
Water flowmeter	±1 percent instantaneous	±0.1 lb/hr (±0.0454 kg/hr)	±2.6 lb/hr at 250 lb/hr (±1.18 kg/hr at 113 kg/hr)
Collector-heater wattmeter	±1/4 percent of full scale	±2 W	±5 W at 1000 W

(c) Electrode efficiency

Run	Emitter temperature, K	Efficiency, η	Limit of error, percent
66-07	1873	0.128	±0.7
45-45	2073	.146	±.7

RESULTS AND DISCUSSION

Efficiency and Power Density

In figure 4, the peak efficiency (defined in the Experimental Procedures) is shown to be relatively insensitive to changes in collector temperature and to exhibit maximums near 950 K collector temperature. If emitter temperature is raised from 1873 to 2073 K, maximum efficiency (defined in (Experimental Procedures) increases from 0.127 to 0.144.

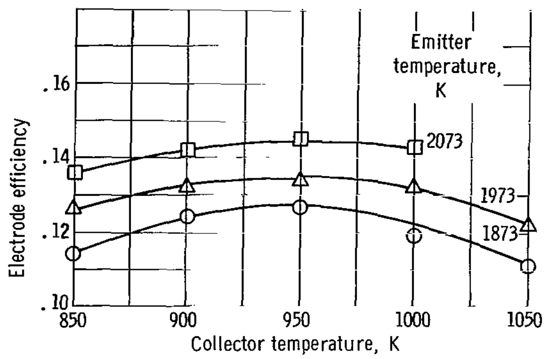

Figure 4. - Variation of peak electrode efficiency with collector temperature.

Electrode power density at peak efficiency is plotted against collector temperature in figure 5 with emitter temperature as a parameter. For any emitter temperature,

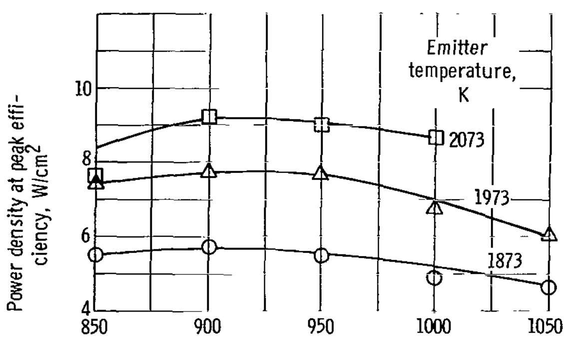

Figure 5. - Power density at peak efficiency as function of collector temperature.

power density is also relatively insensitive to changes in the collector temperature and exhibits a broad maximum near a collector temperature of 900 K. The highest value of power at peak efficiency increases from 5.7 to 9.2 watts per square centimeter when the emitter temperature is raised from 1873 to 2073 K.

The dependence of electrode voltage at peak efficiency on electrode temperature is illustrated in figure 6. Over the range of collector temperatures considered, this voltage is also insensitive to collector temperature changes. For example, at 1873 K emitter temperature, the voltage varies from 0.53 to 0.57 volt as the collector temperature is increased from 850 to 950 K. The voltage at each emitter temperature maximizes near 950 K collector temperature and the maximum increases from 0.57 to 0.85 volt when the emitter temperature increases from 1873 to 2073 K.

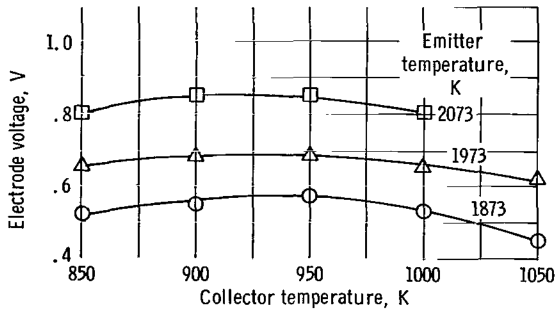

Figure 6. - Electrode voltage at peak efficiency as function of collector temperature.

For an emitter temperature of 1873 K, the peak converter power density obtained by both static and pulse data techniques is plotted in figure 7 against the collector tempera-

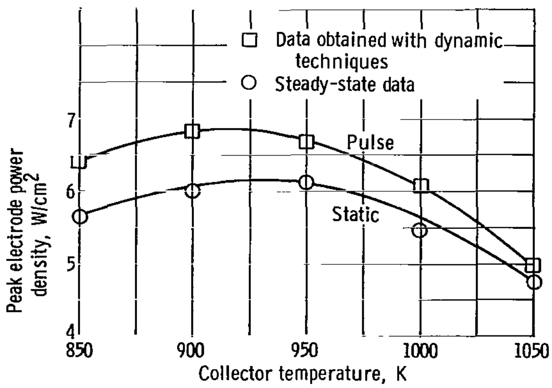

Figure 7. - Peak power as determined by two data taking techniques as function of collector temperature. Emitter temperature, 1873 K.

ture. As previously described in the Experimental Procedure section, a pulse technique was used to determine the cesium-reservoir temperature, electrode voltage and current density corresponding to peak power at each selected emitter-collector temperature combination. However, because of the current limitation of the emitter lead, the steady-state peak power data could be obtained only at the 1873 K emitter temperature.

As determined from the static tests, power density maximizes at a value of 6.2 watts per square centimeter near 950 K collector temperature (fig. 7) which is about 0.6 watts per square centimeter greater than the power density achieved at peak efficiency (fig. 5) for the same electrode temperatures.

The power density values obtained with the pulse technique are consistently higher than those obtained by the static technique, as shown in figure 7. Although the difference is within the experimental accuracy of the measurements, the consistently higher values suggest that the data-taking technique, that is pulse or static, has some effect on the measured performance of the converter. The difference in performance could be attributed, at least in part, to differences in the emitter axial temperature distribution which existed when the data were acquired. For example, when the pulse technique was employed, the emitter axial temperature distribution was adjusted by varying both the ratio of ac to dc input powers and the electrode steady-state voltage until the most uniform emitter temperature possible was achieved. The converter voltage was then pulsed and the current-voltage response was recorded. However, when the static technique was used one degree-of-freedom in control of emitter temperature profile was lost, viz, electrode voltage. The resulting axial temperature gradient may have been of sufficient magnitude to account for at least part of the difference in performance shown in figure 7.

Figure 8 illustrates the loss in efficiency associated with operating the converter at peak output power. As shown, the efficiency at peak power is 0.011 below the maximum efficiency (i.e., 0.116 against 0.127). However, the electrode voltage at peak power is only 0.43 volts (ref. 3) while at peak efficiency it is 0.57 volts.

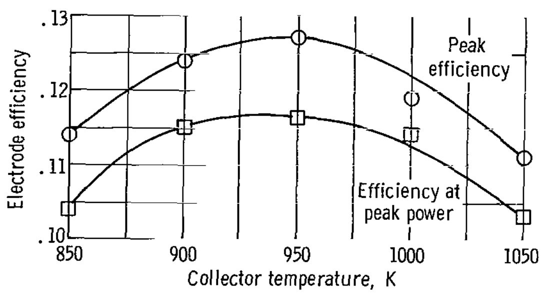

Figure 8. - Electrode efficiency plotted against collector temperature. Emitter temperature, 1873 K.

This discussion has emphasized the dependence of performance characteristics including efficiency and power density on electrode temperatures. Summary plots which illustrate the interplay between various performance characteristics are presented in appendix A, where performance changes are described under operating constraints, which may occur in nuclear reactor power systems.

Heat Balance

The thermal power Q_c delivered to the collector (i.e., by radiation, conduction and electron heating) and the electrical output power IV were measured as functions of current density for emitter temperatures of 1873 and 1973 K and collector temperatures in the range from 850 to 1050 K. The heat flux is presented as a function of current density for a representative case in figure 9 (i.e., an emitter temperature of 1973±25 K, collector temperature of 900±15 K, and a cesium-reservoir temperature of 623±2 K). The input power Q_{IN} is the sum of the filament-heating (ac) and electron-bombardment (dc) powers. For negligible plasma end losses, the net power Q_E leaving the emitter is equal to the sum of the electrical output power, IV, and the collector thermal power, Q_C which is measured calorimetrically. This curve is labeled "measured Q_E" in figure 9.

The curve labeled "predicted Q_E" was obtained by calculating the total power transferred from the emitter to the collector by radiation, conduction and electron cooling. The effective total emittance of the emitter and collector, determined as shown in appendix B, was employed to calculate the total heat radiated. The cesium conduction loss was determined according to the technique outlined in reference 5, based on measured values of emitter, collector and cesium reservoir temperatures. Electron cooling of the emitter is taken as the product of the converter current I and the sum of the average electron kinetic energy (2kT/e) and emitter potential barrier (ψ_E) as determined by the Richardson-Dushman equation. The range of predicted Q_E values shown by the brackets in figure 9 is a result of the designated variations of the electrode and cesium reservoir temperatures.

A plot of collector thermal power Q_C as a function of current density is also shown in figure 9. The line drawn through the data points represents a least-squares fit. The thermal power transferred to the collector per ampere of current, as determined from the slope of this line, is 2.0 watts per ampere. A number of other cases, also considered at emitter temperatures of 1873 and 1973 K, yielded values in the range of 2.1±0.26 watts per ampere.

In general, for converter current densities greater than 5 amperes per square centimeter, the predicted Q_E value (power leaving the emitter) is greater than the measured Q_E value. This difference varies from 0.4 to 0.7 watts per ampere. Similar measure-

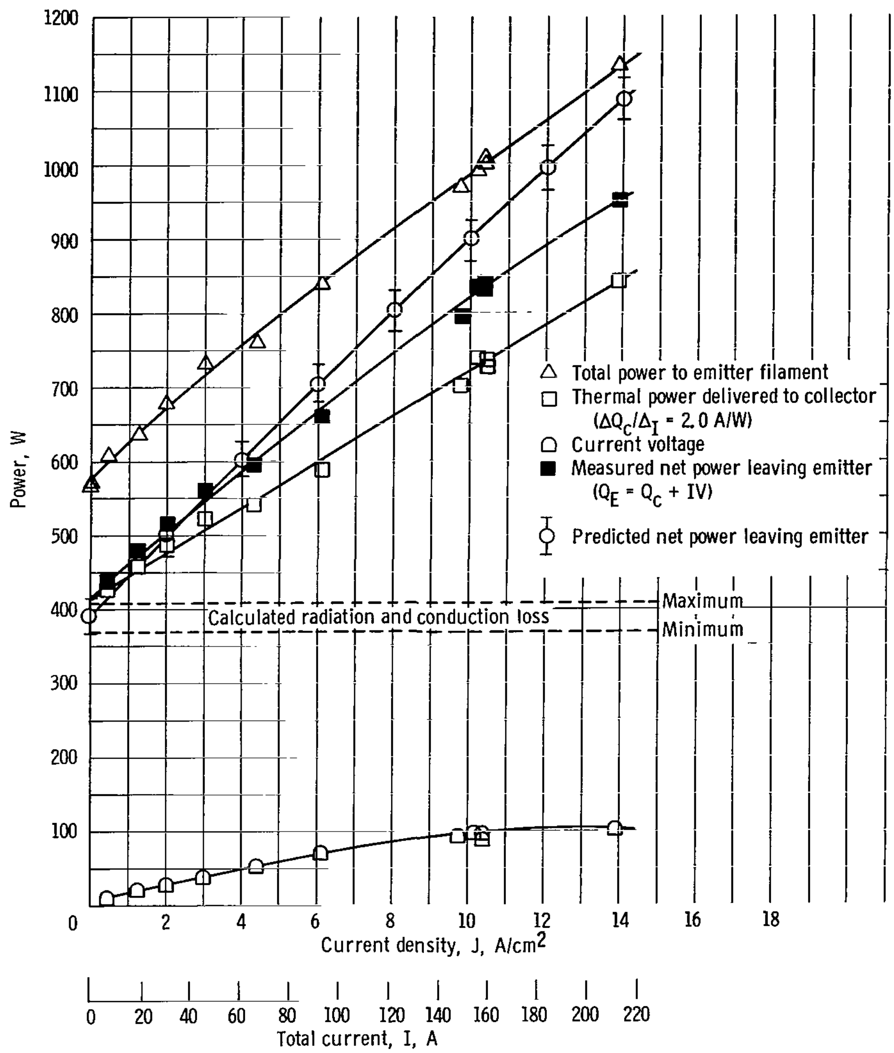

Figure 9. - Comparison of predicted and measured emitter heat flux as function of current density. Emitter temperature, 1973±25 K; collector temperature, 950±15 K; cesium reservoir temperature, 623±2 K.

ments, made on a planar converter having a tungsten emitter and a nickel collector with a 5-mil spacing (ref. 6), resulted in a difference of 0.3 watts per ampere. According to reference 6, this difference probably represents heat that is returned to the emitter by ions, excited atoms, and radiation from the cesium plasma.

The difference between the measured input power Q_{IN} and the electrical and thermal output power, "measured Q_E", (about 175 W in fig. 9), is independent of converter current. This indicates that the sum of the filament and emitter thermal losses are constant for given cesium-reservoir, effective emitter, and effective collector temperatures (i.e., changes in electrode temperature profile associated with changes in converter current have little effect on emitter and filament heat losses).

SUMMARY OF RESULTS

The following results were obtained from the performance evaluation of an electrically-heated cesium-filled rhenium-niobium cylindrical thermionic converter:

1. For the range of conditions studied, the maximum electrode efficiency and the corresponding output power density and electrode voltage are as follows:

Emitter temperature, K	Maximum electrode efficiency,	Power density, W/cm^2	Electrode voltage, V
1873	0.127	5.7	0.57
1973	.135	7.7	.68
2073	.144	9.2	.85

2. The performance listed below was obtained when the converter was operated at maximum power density at 1873 K emitter temperature.

Electrode efficiency	Power density	Electrode voltage
0.117	6.2 W/cm^2	0.43 V

3. The heating of the collector as measured calorimetrically was found to be a function of a diode current, the slope being 21.0±0.26 watts per ampere for emitter temperatures of 1873 and 1973 K.

4. The net power leaving the emitter, which is the sum of the thermal power reaching the collector and the electrical output power, was experimentally measured and compared to predicted values. The values were in agreement for current densities up to about 5 amperes per square centimeter. However, at higher current densities, the measured power was approximately 0.4 to 0.7 watts per ampere less than the predicted values.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 27, 1968,
120-27-05-01-22.

APPENDIX A

EFFECTS OF OPERATING CONSTRAINTS ON CONVERTER PERFORMANCE

Figures 10 and 11 are summary plots of converter performance presented to illustrate the effect of operating constraints which may occur in a reactor power system. In

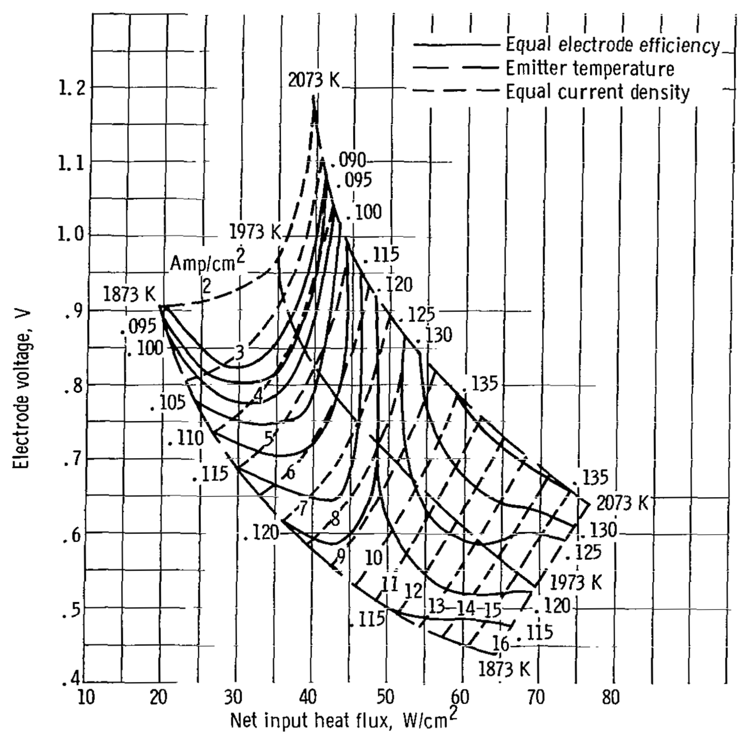

Figure 10. - Effect of variations in input heat flux on electrode voltage and efficiency.

order to construct these plots, all the data obtained in the test program were grouped by emitter temperature, independent of collector temperature. For each of the three emitter temperatures considered, a family of curves for electrode efficiency and power density, each plotted against the electrode voltage, were constructed by least-squares fitting of the data. The data were then replotted in the form of electrode voltage against the net input heat flux, Q_E (figs. 10 and 11). The input heat flux was calculated from the measured converter power density and electrode efficiency.

It should be noted that the curves of figures 10 and 11 maximize at efficiencies and power densities lower than the actual measured maximum values referred to in the pre-

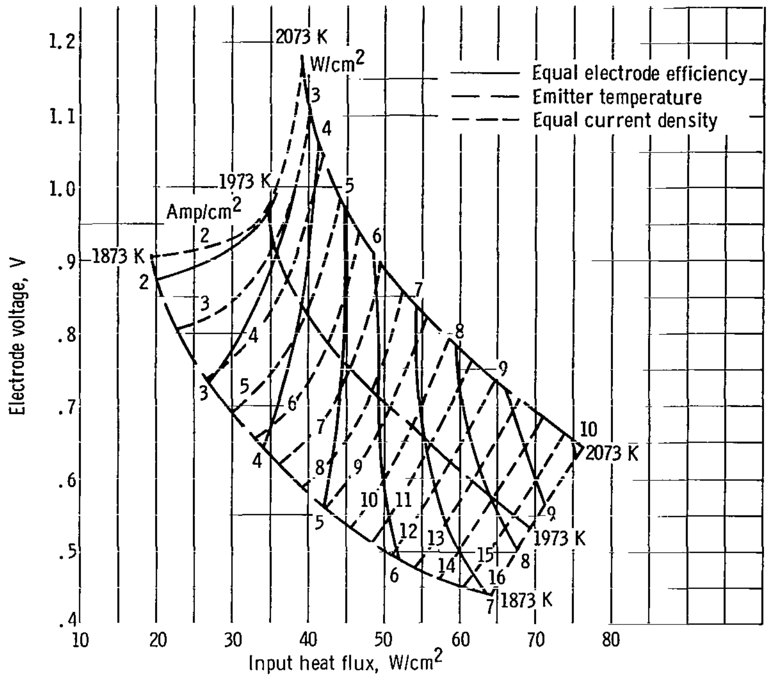

Figure 11. - Effect of variations in input heat flux on electrode voltage and power density.

ceding text; the values are compared in table VI. This results, of course, from the averaging of data for a range of collector temperature (i.e., points of maximum performance were averaged with off-optimum points). Again, the curves were constructed to illustrate the effect of various operating constraints on performance and are representative only in this sense.

Referring to either figure 10 or 11, it can be seen that at a fixed emitter temperature increasing the input heat flux results in a decrease in electrode voltage. This is because the additional input heat can only be transferred by increased electron emission which occurs at the lower voltages.

Similarly if the current density is fixed while the input heat flux is increased, the emitter temperature and the electrode voltage increase. Most of the added power is radiated to the collector while a small portion is converted to useful power.

As shown in figure 10, if the converter is restricted by the power source to a fixed input heat flux in the range from 20 to 45 watts per square centimeter, the electrode efficiency decreases as the electrode voltage is increased. For example, at a fixed input heat flux of 40 watts per square centimeter, an increase in electrode voltage from 0.58 to 1.13 volts (which corresponds to an emitter temperature increase from 1873 to 2073 K), causes a decrease in efficiency from 0.119 to 0.68. Hence, in this range of input heat flux, the converter should be operated at the lowest emitter temperature (i.e.,

TABLE VI. - COMPARISON OF MAXIMUM EFFICIENCY AND CORRESPONDING POWER DENSITY FROM CONSTRUCTED PERFORMANCE MAPS WITH THE MEASURED VALUES[a]

Emitter temperature, K	Values from constructed performance maps			Measured values		
	Maximum efficiency, η_{max}	Power density at η_{max}, W/cm^2	Electrode voltage at η_{max}, V	Maximum efficiency, η_{max}	Power density at η_{max}, W/cm^2	Electrode voltage at η_{max}, V
1873	0.120	4.3	0.62	0.127	5.5	0.57
1973	.126	7.4	.62	.135	7.7	.68
2073	.136	8.7	.74	.146	9.0	.85

[a]See figs. 10 and 11.

1873 K) if converter efficiency is the prime consideration. However, at a fixed heat flux in the range from 45 to 70 watts per square centimeter, increasing the electrode voltage (emitter temperature) increases the conversion efficiency. For example, fixing the input heat flux at 52 watts per square centimeter and increasing the electrode voltage from 0.49 to 0.86 volt (which corresponds to an emitter temperature rise from 1873 to 2073 K), results in a continual improvement in conversion efficiency from 0.115 to 0.125. Hence, in this higher heat flux range, operating the converter at the highest emitter temperature (i.e., 2073 K) results in the highest efficiency and electrode voltage.

Figure 11 illustrates the effect of various converter operating constraints on the output power density. For a fixed input heat flux between 20 and 45 watts per square centimeter, increasing the emitter temperature (by increasing the electrode voltage) decreases the output power density. For example, at 40 watts per square centimeter input heat flux, the output power decreases from 4.7 to 2.7 watts as the emitter temperature is increased from 1873 to 2073 K, while the electrode voltage increases from 0.58 to 1.13 volts. However, for a fixed input heat flux in the range from 45 to 70 watts per square centimeter, the output power density increases as the emitter temperature is raised. This is due to the improved converter efficiency at the higher temperature levels as shown in figure 11.

If the converter is restricted to operate at a fixed voltage, an increase in input heat flux will increase the converter output power and the emitter temperature. If, however, the converter must operate at a fixed electrode temperature, an increase in the input heat flux must be compensated for by decreasing the electrode voltage. Over the operating range shown, this would result in increased output power.

APPENDIX B

ELECTRODE EFFECTIVE EMITTANCE DETERMINATION

The effective total emittance ϵ_{EC} for the emitter-collector surfaces is related to the individual emitter and collector total emittances, ϵ_E and ϵ_C, respectively, by the following equation:

$$\frac{1}{\epsilon_{EC}} = \frac{1}{\epsilon_E} + \frac{1}{\epsilon_C} - 1 \tag{B1}$$

However, since ϵ_E and ϵ_C are not known for this converter, the value of ϵ_{EC} was found experimentally.

In order to determine the net amount of heat transferred from emitter to collector by radiation, the converter was operated under open-circuited conditions and the heat transferred to the collector measured. The cesium reservoir temperature was varied from 373 to 673 K during this test.

The net heat radiated to the collector was then found by subtracting the calculated value of heat transferred to the collector due to cesium conduction, from the total heat measured. The cesium thermal conductivity values were taken from reference 5. The net radiated heat is given as a function of emitter temperature in figure 12 for a fixed mean collector temperature of 900 K. Note that the heat radiated increases from 267 watts at an emitter temperature of 1900 K to 493 watts when the emitter temperature is increased to 2100 K. The effective total emittance ϵ_{EC} can then be found by using equation (B2) for a given value of emitter and collector temperature.

$$\epsilon_{EC} = \frac{Qrad_{EC}}{\sigma\left(T_E^4 - T_C^4\right)\times 15.2} \tag{B2}$$

For an emitter temperature of 1973 K and a collector temperature of 900 K, the effective emittance is 0.271. Since reported values of rhenium and niobium emittance vary somewhat and also because of the dependence of emittance on surface roughness, the possible values of collector (niobium) emittance were plotted as a function of emitter (rhenium) emittance for the above conditions of emitter and collector temperature in figure 13. If 0.315 is used as the rhenium emittance, as reported in reference 7, a corresponding niobium emittance of 0.665 results as shown in figure 13. This value is much higher than the reported value for niobium. It is interesting to note that similar results were reported in reference 4.

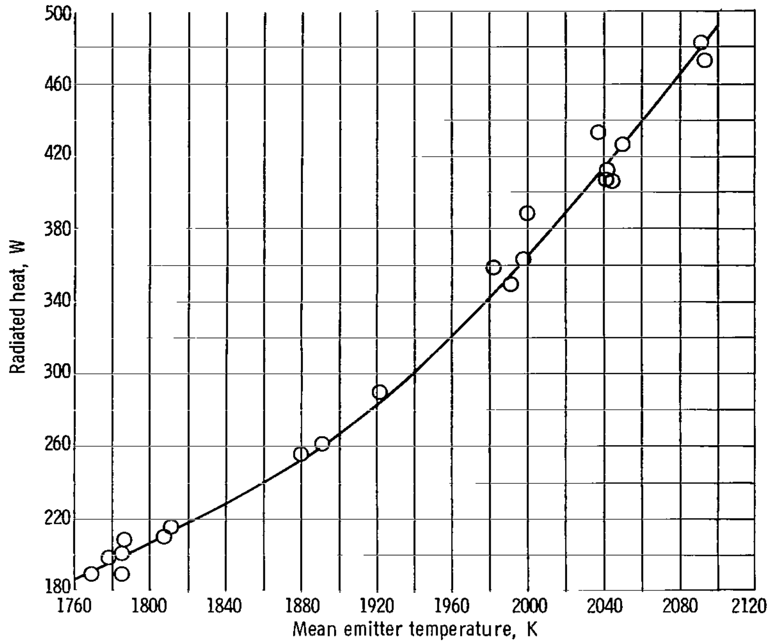

Figure 12. - Heat transferred by radiation from emitter to collector as function of emitter temperature for effective collector temperature of 900 K.

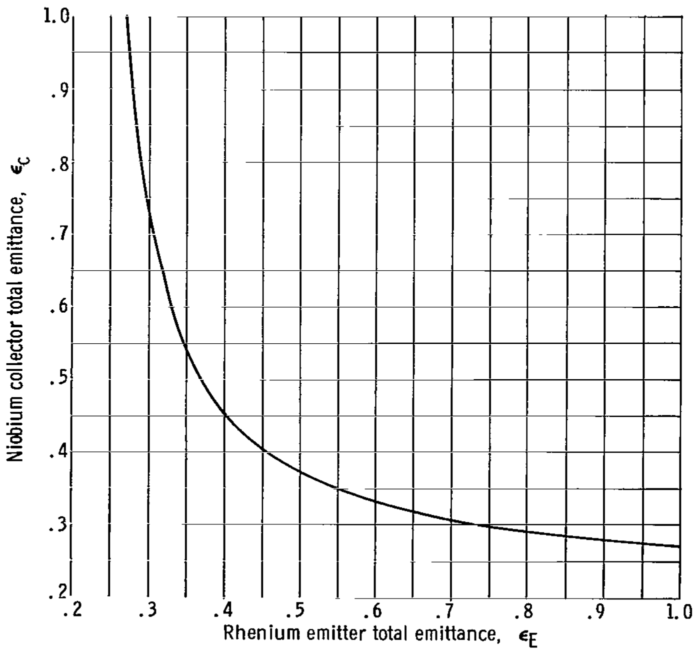

Figure 13. - Niobium emittance as function of rhenium emittance for effective total emittance of 0.271.

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